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Life cycle assessment of a building added concentrating photovoltaic system (BACPV)

Karim Menoufi[a]*, Daniel Chemisana[b], Joan I. Rosell[b]

[a]*Renewable Energy Sciences and Engineering Department, Faculty of Postgraduate Studies for Advanced Sciences, Beni-Suef University, Beni-Suef 62511, Egypt*
[b]*Universitat de Lleida, Calle Pere de Cabrera S/N, Lleida 25001, Spain*

Abstract

This article compares the environmental and energy performance of a novel Building Added Concentrating Photovoltaic (BACPV) system to a conventional Building Integrated Photovoltaic (BIPV) system through their entire life cycle. We have found that the overall life cycle environmental impact of the BACPV system is a factor of 1.5 lower than that of the BIPV system. Referring to the energy profile, the Energy Payback Time of the BACPV system has been estimated as 1.0 year, while that of the BIPV system has been estimated as 2.2 years. Similarly, the Energy Return Factor is 32 for the BACPV system and 14 for the BIPV system. Additionally, suggestions for improvements for the BACPV system are proposed. This is mainly summarized in modifying the design through replacing some system components.

Keywords: life cycle assessment (LCA); building added concentrating photovoltaic (BACPV); environmental impact; concentrating photovoltaics; reflectors

* Corresponding author. Tel.: +2 012222 80 481 fax: +20 82 22 44 136.
E-mail address: karim_menoufi@hotmail.com

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1. Introduction

Photovoltaic (PV) electricity generation is a zero-emissions process. However, the manufacturing of PV systems causes impacts on the environment. Concentrating Photovoltaic (CPV) systems are mainly composed of simple lenses or reflectors that focus the solar radiation on smaller PV cell areas. For this, they offer promising opportunities to further reduce the environmental impact and embodied energy during the assembly phase [1].

The present article presents a LCA study of a novel low concentration BACPV system, with a maximum achieved concentration ratio of 10 suns. This system was assembled and analyzed at the Applied Energy Research Centre (CREA) at the University of Lleida (Spain). This BACPV system is comparable to a previously studied Building Integrated Concentrating Photovoltaic (BICPV) system [1] at the University of Lleida, where it is considered as a modification of it. This modification is manifested in integrating the reflectors to the building as a shading system, (instead of being integrated vertically as a façade) with an inclination of 50º with respect to the horizontal plane.

Nomenclature

BIPV	Building Integrated Photovoltaic
BACPV	Building Added Concentrating Photovoltaic
BICPV	Building Integrated Concentrating Photovoltaic
LCA	Life Cycle Assessment
CED	Cumulative Energy Demand
EPT	Energy Payback Time
ERF	Energy Return Factor
PV	Photovoltaic
CPV	Concentrating Photovoltaic
Pt	Point

2. System description

2.1. BACPV system

The BACPV system is composed of a concentrating system and CPV modules. The concentrating system consists of 17 flat coated reflectors (2.6 x 0.05 x 0.003 m), with a maximum concentration ratio of 10 suns, (Fig. 1). A steel structure is used as a frame for the concentrating system in order to hold it and position it in place. An actuator (LINAK LA 12 [2]) is connected to two moveable steel parts passing through the middle of the reflectors plane for the purpose of sun tracking adjustments.

Fig. 1. The concentration system used: Assembled at the applied physics laboratory at the University of Lleida (Spain).

Two CPV modules (Fig. 2), 250 Wp each (1.125 x 0.12 m^2), which were previously assembled and characterized [3, 4] are put in use to be the receiver units. Each CPV module consists of a 300 microns thickness sheet of single crystalline silicon CPV cell (52 cells, 48 x 36 mm each) manufactured by Narec Solar [5]. The CPV cells are insulated with a thermal tape (Thermattach T-404 [6]) of 127 microns thickness. A cooling structure is installed, where it is composed of a copper U- shaped support that holds the CPV cells and the thermal tape internally, while allowing the passage of two copper cooling pipes from beneath. The cooling pipes are externally connected to a 5 watt water pump. The whole system is enclosed within an aluminum frame box, and covered by two transparent white glass sheets, placed at the top and the bottom.

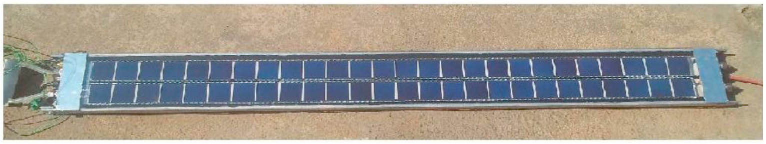

Fig. 2. The CPV modules: Assembled at the applied physics laboratory at the University of Lleida (Spain).

The BACPV system was installed and characterized following the procedures detailed previously in Amrizal et al. [3, 4] during a one year period from January to December 2012. The BACPV system was set into operation considering the fulfillment of two functions: The energy output to be optimum for the city location (Lleida, Spain), and to act as a shading screen. Under these requirements, the reflectors platform tilt angle which best suited both functions was found to be 50º with respect to the horizontal plane. Besides, the reflectors length was selected to be 15 % larger than that of the modules in order to minimize the contour effects due to the hourly sun movement. The BACPV system annual energy output registered was 444 kWh/year.

2.2. BIPV system

In reference to the compared BIPV system, it consists of two PV modules achieving the same power of the CPV ones (250 Wp each) from Isofoton [7]. Each module is made up of a 200 microns sheet of single crystalline silicon PV cells (60 cells, 156 x 156 mm each). The PV cells are encapsulated with two 300 microns layers of PVB (Poly Vinyl Butyral), and surrounded by two transparent white glass sheets. The configuration is supported by an aluminum framework. The system was experimentally characterized under the same conditions of the BACPV system and the annual energy output was found as 824 kWh/year. It is observed that the BIPV system produced around 1.8 times more energy output than the BACPV system. This is attributed to the geometry of the concentrator with respect to two aspects: First, the BACPV module only partially received the concentrating irradiance beam due to contour effects; and second, the concentrator acceptance angle limited the operational daily time, affected by the solar height.

2.3. System boundaries

For the LCA, the functional unit used is 1 kWh (the environmental impact and energy profile are represented per kWh), where kWh is referring to the electricity produced by each system during its entire lifetime. A service lifetime of 30 years is assumed for both of the BACPV and BIPV systems. In addition, an average degradation rate throughout the whole life time of the corresponding PV and CPV modules of 2.5 % per year is assumed, taking into consideration the average range of values present in literature [8]. Two life cycle phases are taken into consideration: The assembly phase that comprises the systems components (extraction, manufacturing, etc.), and the operational phase. The environmental impact of water consumption used for occasional cleaning has been found insignificant. However, such assumption would have a significant impact within large scale PV systems that could utilize massive quantities of water for cleaning. The operational phase is represented by the electricity produced by each system, where it is a green electricity coming from a photovoltaic technology with no emissions. Hence, in order to evaluate the full life cycle of the two systems, the environmental impact and the energy profile are represented per kWh of electricity produced by each system through their entire life span. The disposal phase is not taken into consideration as no certainty about the post consumption phase was found after 30 years of service lifetime.

For simplification purposes, the transportation was excluded. Previous studies showed that the transportation does not significantly influence the environmental impact and embodied energy, ranging from 0.2 % to a maximum contribution of 2 % of the total [9–11] and only reaching 6 % in a specific case study, where the transportation included importing several parts of the corresponding PV systems from Asia to Europe [12].

3. Methodology

The LCA study in this article is evaluated using two complementary LCA techniques: The ReCiPe methodology [13] for evaluating the environmental profile, and the Energy Return Factor (ERF) and the Energy Payback Time (EPT) for evaluating the energy profile. For the assembly phase, the environmental profile has been evaluated based on the Eco-Invent database [14], where the inventory data of the corresponding systems (Table 1) have been gathered and calculated at the experiment site, and then correlated with the Eco-Invent database and the corresponding environmental models of the chosen methodologies. Similarly, for the energy profile analysis, the Cumulative Energy Demand (CED) has been evaluated. The LCA (including both the environmental and energy profiles evaluations) has been evaluated considering the assembly phase and the operational phase, where the latter phase has been taken into consideration through measuring the electrical energy of the two corresponding systems throughout a whole year. Then, the overall electrical energy produced by the two corresponding systems throughout their entire lifetime has been estimated, taking into consideration the assumed value of degradation rate as mentioned above. After that, by choosing the functional unit as 1 kWh (mentioned previously), the environmental profile LCA results are presented as the environmental impact per kWh of electricity produced by each system through their entire lifetime. The energy profile results are presented per kWh as well (in case of evaluating the CED). Additionally, both the EPT and ERF are dependent on the CED and the electricity produced by the two systems during their entire lifetime as well.

Table 1. Life Cycle Inventory of the studied systems.

Item description/function	Materials used	Quantity (kg)
BACPV system		
CPV cells	Single-Crystalline Silicon	0.13
Insulation (Thermal tape)	Thermattach (T404)	0.02
CPV module cover	White glass	2.87
CPV module frame	Aluminum	5.15
Cooling pipes	Copper	1.14
U – Shaped support	Copper	1.01
Water pump	Steel	1.5
Reflectors	Float coated glass	17.24
Reflectors frame	Carbonated steel	61.92
Reflectors covers	White glass	81.12
Actuator gear	Steel	1
Actuator housing	Reinforced plastic	0.5
BIPV system		
PV cells	Single-Crystalline Silicon	1.36
Encapsulation	EVA (Ethyl Vinyl Acetate)	2.13
Cover	White glass	53.02
Frame	Aluminum	40.96

3.1. Recipe

The environmental profile evaluation was achieved using the ReCiPe methodology [13] (v 1.08, the Hierarchist perspective) in conjunction with the Eco-Invent database (v2.2) (v 7.3.3) [14]. The ReCiPe methodology considers so-defined midpoint indicators which describe the environmental effects on an intermediate position on the environmental cause-effect chain, and endpoint indicators referring to three areas of protection: human health, ecosystem quality, and natural resources. The latter endpoint indicators express the severity of the contribution of the impact categories to the environmental load (Higher score of a product or a specific component means higher impact on the environment) through the environmental impact points (Pt). These points are regarded as dimensionless figures. That is, their absolute value is not very relevant, as the main purpose is to compare relative differences between products and components.

3.2 Energy Return Factor (ERF)

The Energy Return Factor (ERF) provides a numerical quantification of the benefit gained out of the exploitation of an energy resource in terms of how much energy is gained from an energy production process compared to how much of that energy (or its equivalent) is required to extract, process, deliver, and otherwise upgrade that energy to a socially useful form [15]. In the case of electricity generation technologies, the ERF entails the comparison of the electricity generated to the amount of primary energy used in different life cycle phases. The ERF is calculated as the ratio of energy delivered to energy costs, and given as follows in Eq. (1):

$$ERF = \frac{\mathrm{E_{global}}}{\mathrm{CED}} \tag{1}$$

Where E_{global} is the sum of the total primary energy output produced during the system entire life time ($MJ_{primary}$). E_{global} was calculated by converting the electrical energy output produced by each system from kWh to $MJ_{electrical}$ (1 kWh = 3.6 $MJ_{electrical}$) and subsequently converting the electrical energy ($MJ_{electrical}$) produced into its primary form ($MJ_{primary}$) via a conversion factor of 0.35 $MJ_{electrical}/MJ_{primary}$ [15]. CED is the Cumulative Energy Demand, which is an indicator used to quantify the direct and indirect energy use throughout the life cycle of a product or a process, including the energy consumed during the extraction, manufacturing and disposal of the materials, valued as primary energy during the complete life cycle of products ($MJ_{primary}$). The CED values for the BACPV and BIPV systems were calculated using the CED methodology (v1.08).

3.3 Energy Payback Time (EPT)

The Energy Payback Time (EPT, in years) is defined as the time needed for a PV system to generate the total energy that was invested during its production as given in Eq. (2):

$$EPT = \frac{\mathrm{LT}}{\mathrm{ERF}} = \frac{CED}{E_{global}/LT} \tag{2}$$

Where LT is the lifetime (30 years) and ERF is the energy return factor of the corresponding system (dimensionless).

4. Results and Discussions

By considering the whole life cycle per 1 kWh of electrical energy output produced by each system (Fig. 3), the BACPV system shows a better environmental performance than the BIPV one. That is, the environmental impact of the BACPV system is a factor of 1.5 lower than that of the BIPV system. Although the BIPV system produces higher energy output during the entire systems lifetime, the BACPV system shows a better overall environmental performance. This is mainly related to the reduced surface area of PV cells employed within the BACPV system in comparison to the BIPV system. Hence, the lower energy output of the BACPV system during the operational phase is more than compensated by its lower environmental impact during the assembly phase, leading to a lower overall life cycle environmental impact score. It is also shown that the Resources damage category of the BACPV system is higher than that of the BIPV one. This is mainly related to the extensive use of metals within the BACPV system, especially copper, which in return affects the depletion of resources (metals), represented through the Resources damage category.

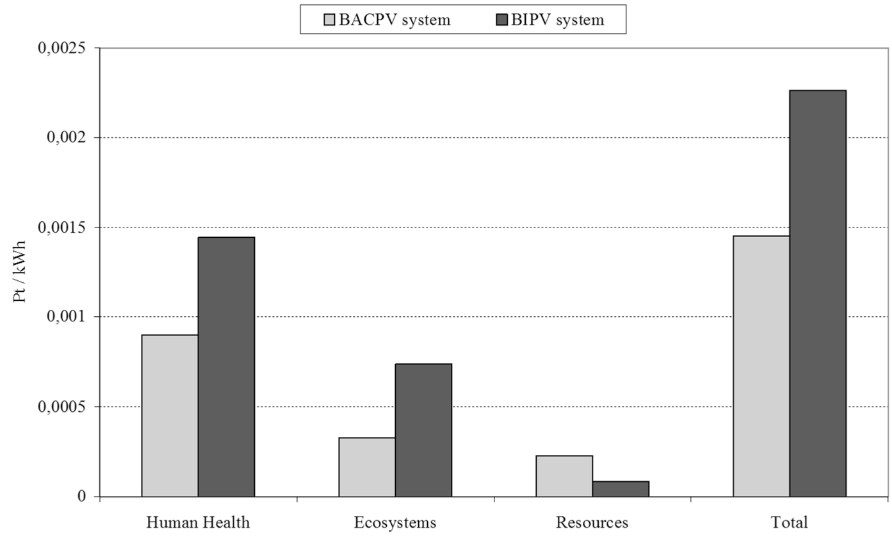

Fig. 3. Relative endpoint damage assessment of both of the BACPV and BIPV systems throughout their entire life cycle using the ReCiPe methodology.

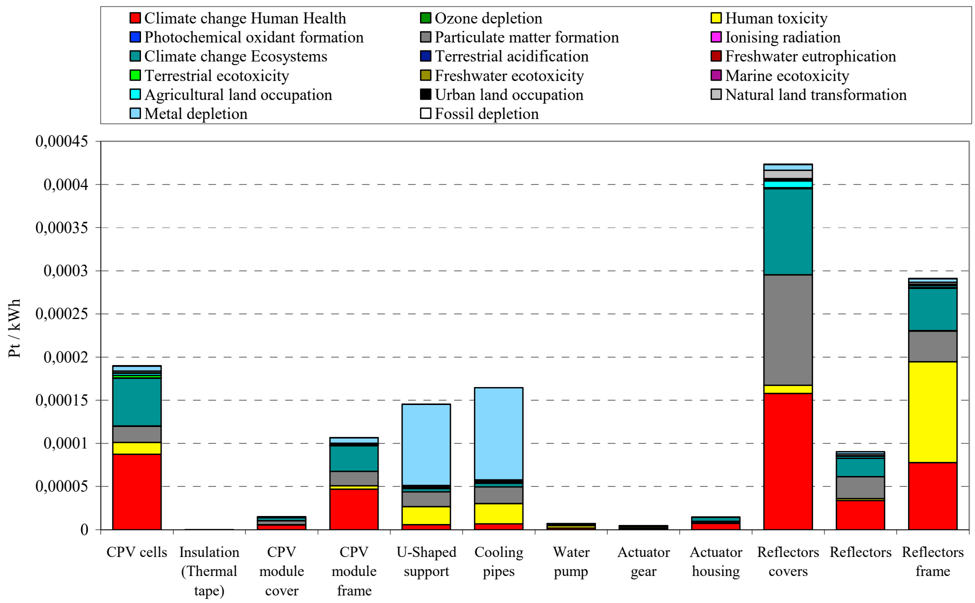

Fig. 4. Relative endpoint damage assessment of the BACPV system components throughout its entire life cycle using the ReCiPe methodology.

A closer look at the environmental impact of the novel BACPV system through examining the individual components is shown in Fig. 4. It is noticed that the principal components of the BACPV system (the CPV cells and the reflectors) contribute by only 13 % and 6 % to the total impact score, respectively. On the other hand, it is observed that the other components (reflectors covers and reflectors frame) contribute by 29 % and 20 %, respectively. Moreover, it is shown that the cooling structure (copper cooling pipes and U-Shaped support) contribute by around 21 % to the total impact score (dominated by the metal depletion impact category). This analysis shows that improving these aspects in the assembly phase would further improve the environmental performance of the BACPV system over its entire life cycle.

Regarding the CED values, they were found as 3087 MJ_{prim} and 12592 MJ_{prim} for the BACPV and BIPV systems, respectively. The ERF was found as 32 for the BACPV system and 14 for the BIPV system. This implies that with the energy generated by the corresponding systems, the BACPV system and the BIPV system can be produced 32 and 14 times, respectively. Additionally, the EPT of the BACPV system is 1.0 years, while the EPT of the BIPV system is 2.2 years.

Fig. 5 shows the contribution of the BACPV system components to the total primary energy demand. It is observed that the CPV cells and the reflectors contribute by 20 % and 8.5 % to the total primary energy demand, respectively. Furthermore, the contributions of the reflectors covers and reflectors frame are found to be the highest (36 % and 17 %, respectively).

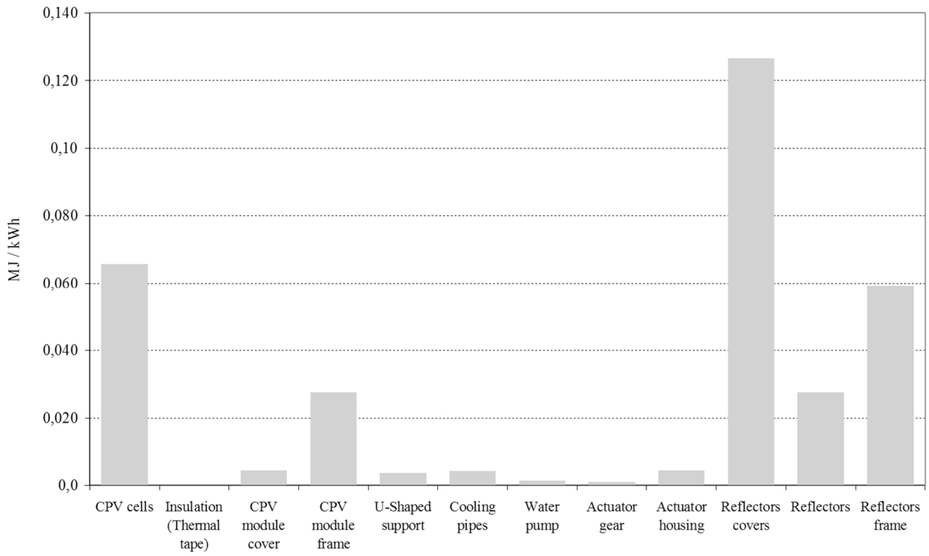

Fig. 5. The contribution of the BACPV system components to the total primary energy demand.

5. Conclusions

A LCA study of a BACPV system at the University of Lleida (Spain) was conducted. The results were compared to those of a conventional BIPV system under the same conditions. The BACPV system shows a better environmental and energy performance throughout the entire systems life cycle compared to the BIPV system. Regarding the novel BACPV system, it was found that the reflectors covers, the cooling structure (cooling pipes and U-shaped support), and reflectors frame constitute the majority of the environmental impact and energy demand. Accordingly, although the BACPV system outperforms the BIPV one from environmental and energy profiles viewpoints, some aspects could be improved. For the assembly phase, reducing or totally replacing the protective covers, the reflectors frame, the copper cooling pipes and the U- shaped support would reduce the environmental impact and the CED as well. The reduction of the CED would consequently leads to lower values of EPT and higher values of ERF. In reference to the operational phase, increasing the surface area of the CPV cells per module would lead to higher energy output as well, contributing in further enhancing the life cycle environmental and energy profiles. Nevertheless, such suggestion is needed to be verified experimentally within newer foreseen designs for the system assembly.

Acknowledgements

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